Is the cosmic UV background fluctuating at redshift $z \simeq 6$?

Jiren Liu[1,3], Hongguang Bi[2], Long-Long Feng[1,4] and Li-Zhi Fang[2]

ABSTRACT

We study the Gunn-Peterson effect of the photo-ionized intergalactic medium(IGM) in the redshift range $5 < z < 6.4$ using semi-analytic simulations based on the lognormal model. Assuming a rapidly evolved and spatially uniform ionizing background, the simulation can produce all the observed abnormal statistical features near redshift $z \simeq 6$. They include: 1) rapidly increase of absorption depths; 2) large scatter in the optical depths; 3) long-tailed distributions of transmitted flux and 4) long dark gaps in spectra. These abnormal features are mainly due to rare events, which correspond to the long-tailed probability distribution of the IGM density field, and therefore, they may not imply significantly spatial fluctuations in the UV ionizing background at $z \simeq 6$.

Subject headings: cosmology: theory - early universe - intergalactic medium

1. Introduction

Recent observations of the absorption spectra of the highest redshift quasars show very strong Gunn-Peterson(GP) troughs at $z \simeq 6$ (Fan et al. 2002; Songaila & Cowie 2002; White et al. 2003; Songaila 2004; Becker et al. 2006; Fan et al. 2006). The spectra are found to be dramatically different from low redshift ($2 < z < 4$) samples. First, the blue sides of the Lyα emission lines are almost completely absorbed, indicating very high absorption optical depths; and second, there are long flux dark gaps of about tens of Mpc separated by tiny light leaks in the spectra. It has been suggested that these observations indicate the end stage of reionization at redshift $z \simeq 6$.

[1]Purple Mountain Observatory,Nanjing, 210008, P.R. China.

[2]Department of Physics, University of Arizona, Tucson, AZ 85721

[3]Center for Astrophysics, University of Science and Technology of China, Hefei, Anhui 230026, P.R. China

[4]National Astronomical Observatories, Chinese Academy of Science, Chao-Yang District, Beijing 100012, China

In low redshift range, $z < 4$, Lyα forests can be explained by absorptions of fluctuated neutral hydrogen atoms in the IGM with a uniform UV ionizing background (e.g. Rauch 1998). In this model, about 80% of the baryons are associated with observed Lyα forest features, while 10% are in the smaller column densities which are not detectable and the other 10% are in collapsed objects (e.g. Bi & Davidsen 1997).

If the distribution of the IGM is uniform and the ionizing background is independent of redshift, the photoionization equilibrium requires the mean optical depth $\tau \propto n_{\rm HI}/H(z) \propto n^2/H(z) \propto (1+z)^{4.5}$, where n is the number density of the IGM, and $H(z)$ is Hubble parameter. One can then expect larger Gunn-Peterson troughs at higher redshift. The current observations show, however, that the mean optical depth actually underwent a much faster evolution at $z \simeq 6$ than the $(1+z)^{4.5}$ relation. To explain this fact it was suggested that the UV background has a strong evolution around $z \simeq 6$. Moreover, the observed Gunn-Peterson troughs are characterized remarkably by a large scatter in statistics. For example, some spectra show complete absorptions while some others show apparent transmissions. The scatter is proposed to be due to the existence of a significantly fluctuating UV background at $z \simeq 6$ (Fan et al. 2006).

Recently, there are a number of simulations or semi-analytical models aiming at the GP effect at those redshifts (e.g. Razoumov et al. 2002; Gnedin 2004; Pascho & Norman 2005; Wyithe & Loeb 2005; Kohler et al. 2005; Gallerani et al. 2006). Those studies generally concluded that the UV background or photoionization rate should be rapidly decreasing toward $z > 6$. However, it is inconclusive on whether a significant inhomogeneity in the UV background is necessary. Lidz et al. (2006) correctly pointed out that transmission spectra are sensitive to rare big voids, and therefore, the observed scatter in optical depths can be produced from density fluctuations without assuming an inhomogeneous UV background. However, it is unclear whether the long-tailed distributions of transmitted flux and long dark gaps can also be explained by their simulation, because the size of their simulation box is closer or even smaller than the scales of dark gaps in quasar spectra, which can be as large as a few tens h^{-1}Mpc. Therefore, the problem of inhomogeneous UV background is still under a cloud.

There are, at least, two other reasons to motivate us to reconsider this problem. First, the redshift dependence of the mean mass density is $\rho \propto (1+z)^3$, and then $\delta\rho/\rho \simeq 3\delta z/(1+z)$. Thus, a mass density fluctuation $\delta\rho$ on large scales is approximately equivalent to a variation in redshift or in wavelength δz. Therefore once there is strong evolution of $\tau(z)$ on redshift, i.e., $d\ln\tau(z)/dz \gg 1$, the fluctuations of density $\delta\rho$ on large scales will yield large variations of τ, even when the UV background is uniform. Second, when the GP depth is very large, the only regions which are left with leaking lights are rare void events in the random field. Those rare events are described by the long-tailed PDF of the IGM density field. The long tails in the lognormal model is found to fit well with high order statistics of the Lyα transmitted flux (Feng & Fang 2000, Zhan et al. 2001, Feng et al. 2001, 2003, Jamkhedkar et al. 2000, 2003, 2005). Therefore, it is worth to study the effect of the rare events in the lognormal model at high redshifts. Because it is a semi-analytical model, we can take 1-D simulations with spatial ranges as large as a few hundreds h^{-1}Mpc, and resolutions as fine as a tenth of the Jeans length (a few h^{-1}kpc).

2. Method of simulations

We simulate Lyman series absorption spectra of QSOs between $z = 3.5$ and 6.4 using the same lognormal method as those for low redshifts $z \simeq 2 - 3$ (e.g., Bi et al. 1995; Bi & Davidsen 1997). In this model, the density field $\rho(\mathbf{x})$ of the IGM is given by an exponential mapping of the linear density field $\delta_0(\mathbf{x})$ as

$$\rho(\mathbf{x}) = \bar{\rho}_0 \exp[\delta_0(\mathbf{x}) - \sigma_0^2/2], \tag{1}$$

where $\sigma_0^2 = \langle\delta_0^2\rangle$ is the variance of the linear density field on scale of the Jeans length. In this model, the peculiar velocity field is also produced by a Gaussian random field, for which the relevant parameteres are selected to make the statistical relation between density and velocity fields follow the predictions of linear fluctuation theory (Bi & Davidsen 1997; Nusser & Haehnelt 1999; Choudhury et al. 2001; Gallerani et al. 2006).

The dynamical bases of the lognormal model have gradually been settled in recent years. First, although the evolution of cosmic baryon fluid is governed by the Naiver-Stokes equation, the dynamics of growth modes of the fluid can be sketched by a stochastic force driven Burgers' equation (Gurbatov et al. 1989; Berera & Fang 1994; Matarrese & Mohayaee 2002). On the other hand, the lognormal field is found to be a good approximation of the solution of the Burgers' equation (Jones 1999). The one-point distribution of the cosmic density and velocity fields on nonlinear regime are consistent with lognormal distribution (e.g. Kofman et al. 1994, Hui et al. 2000, Yang et al. 2001, Pando et al. 2002). Especially, it has been shown recently that the velocity field of the baryonic matter of the standard ΛCDM model is well described by the so-called She-Lévěque's universal scaling formula, which is given by a hierarchical process with log-Poisson probability distribution (He et al. 2006).

As mentioned in §1, our purpose is to study whether the observed Lyman absorptions of QSOs at high redshifts can really rule out models with a uniform UV background. Therefore, we assume that the UV background is spatially uniform, contributed by QSOs and active galaxies, and is represented by an photoionization rate $\Gamma_{\rm HI}$, which is allowed to change in the redshift range $3.5 < z < 6.4$. The baryonic gas is heated by the UV background. The thermodynamical properties of the IGM are actually complicate, because nonlinear evolution leads to a multi-phased IGM. For a given mass density, the temperature of the IGM can be different by 1 to 2 orders (He et al. 2004). Nevertheless, the IGM temperature is related to mass density by a power law $T \propto \rho^a$ in the density range $\rho/\bar{\rho} < 5$, $\bar{\rho}$ being the mean density (see also Hui & Gnedin 1997). The neutral fraction is solved under photoionization equilibrium assumption. To consider the peculiar velocity effect and thermal broadening, we do a convolution of the neutral hydrogen density and velocity field with Voigt profile. This yields the absorption optical depth.

We use the standard ΛCDM cosmological model that is generally accepted in this type of studies and consistent with the new WMAP data (Spergel et al. 2006): $\Omega_{DM} = 0.3$, $h = 0.74$, $\sigma_8 = 0.82$, $\Omega_b h^2 = 0.025$ and $a = 1/3$. The temperature at the mean density is $1.3 \times 10^4 K$ and there is a cut-off of the minimal temperature at $10^4 K$. In redshift space, the size of the simulation samples is given by $z - 0.3$ to $z + 0.3$. There are 2^{14} pixels in each redshift range $z \pm 0.3$. We produced 1000 samples for $3.5 < z < 5$, and 2000 for $5 < z < 6.4$, so as to get the GP depth and their variance. When comparing to relevant observations, we have divided the samples to sub-samples with about the same redshift interval (which is 0.15 in Fan et al. 2006), properly smoothed the mock spectra with observational resolution and added instrumental noise.

3. Simulation Results

1. *GP optical depth.* We first try to fit the strong evolution of the GP optical depth $\tau(z)$ of Lyα absorption. This can easily be done if we take the photoionization rate to be

$$\Gamma_{\rm HI}(z) = 7 \exp\{-[(1+z)/(1+z_0)]^3\} \tag{2}$$

where $\Gamma_{\rm HI}$ is in unit of 10^{-12} s^{-1}, z_0 being a free parameter. Eq.(2) shows that $\Gamma_{\rm HI}(z)$ undergoes a strong evolution when $z > z_0$, probably due to a strong evolution of star formation rates. This model is consistent with the general argument that collapsed objects underwent a fast evolution at larger redshifts (Bi et al. 2003). We found that $\tau(z)$ in redshift range $3.5 < z < 6.4$ can be well fitted by eq.(2) if the fitting parameter z_0 is in the range 3.0 - 3.2. The result is shown in Figure 1, and the observed data are taken from Songaila & Cowie (2002) and Fan et al. (2006).

The resultant neutral fraction is about 2.2×10^{-4}, 8.2×10^{-4} and 2.6×10^{-3} at $z = 5.5, 6.0$ and 6.4 in the $z_0 = 3.0$ model, and 1.2×10^{-4}, 4.0×10^{-4} and 1.1×10^{-3} in the $z_0 = 3.2$

model.

2. *Variance of GP optical depth.* Figure 2 presents the variance of $\tau(z)$ from an ensemble of 1000 ($3.5 < z < 5$) or 2000 ($5 < z < 6.4$) simulation samples. They are in good agreement with observed data (Fan et al. 2006), also shown in Figure 2. When we look into the details of simulation samples, we found the scatter is really large. That is to say, the ensemble of simulated spectra contains samples of complete absorption as well as samples of apparent transmission. The optical depth is very sensitive to the density fluctuations when the average GP optical depth is large. Around $z = 6$, the average transmission is basically contributed by lights leaking from only a few low density voids in the fluctuating density field. They are rare evens, but they are not negligible if the PDF of the density is long-tailed. In other words, the variance of the optical depth mainly depends on long-tailed low-density events. If a physical phenomenon biases to rare events, the variance generally is large.

3. *PDF of flux.* Figure 3 presents the probability distributions of the transmitted flux of Lyα absorption at redshifts $z = 5.5$, 5.7 and 6.0. The observed data are from Fan et al. (2002). Here we use the simulation size of 0.24 in redshift, smooth the simulated spectra by a Gaussian instrument of resolution 2600 and then binned them into pixels of 35 km s^{-1}, which are about the same as observation. We also add noises in the simulated spectra. The result shows again that the simulated distributions of the flux are in good agreement with observations. Figure 3 shows that most pixels have only very small transmitted flux, which correspond to opaque regions in spectra. Figure 3 also shows that although the spectra are general opaque, there do exist rare but not negligible high transmitted flux. The long-tail is typical for a lognormal random field. Figure 3 is consistent with Fig. 2 that the observed large scatter of the GP optical depth could be caused by the fluctuations of the IGM density field, not necessarily by irregularities in the spatial distribution of the UV background.

4. *Dark gaps.* In Figure 4, we present the evolution of mean dark gaps as a function of redshift. The dark gap is defined as the continuous region in which all pixels have optical depth larger than 2.5. The mean dark gap from the simulations has a strong evolution at $z > 5.4$, and is generally consistent with observations. However, we note that the gap at high redshift is sensitive to the smoothing. If we use the original spectra without instrumental effects, the mean dark gap is smaller than that with smoothing. This is because light leaking areas, which are used to define the boundaries of the gaps, are very small and show up as spikes in spectra. Therefore, they will disappear if take a smoothing on larger scale. Figure 4 shows that the significant increase of dark gap size at $z \simeq 6$ can also be reproduced by the strong evolution of $\tau(z)$ alone.

4. Discussions and Conclusions

We show that the lognormal model can uniformly and reasonably explain the observed statistical properties of the Lyα GP absorption at high redshifts $5 < z < 6.4$, if the intensity of the uniform UV background, undergoes a strong evolution around $z > 5$. The large scatter of optical depths and large dark gaps are resulted naturally from the strong evolution of the optical depth. These abnormal features may not imply the existence of significantly spatial fluctuations in the UV ionizing background. Of course, fluctuations of the UV ionizing background with power less than the density perturbations are possible in this model.

It is interesting to compare the strong evolution of the optical depth $(d \ln \tau/dz) \gg 1$, with phase transition. The condition $(d \ln \tau/dz) \gg 1$ is typical in phase transition when the IGM transits from the state (phase) of opaque to transparency with the decrease of the UV background. It likes phase transition due to the increase of pressure. Around the point of phase transition, the long wavelength perturbations will cause large fluctuations in the system considered. For instance, a normally transparent medium appears milky at critical point due to the correlations caused by long wavelength fluctuations. At redshift $z > 6$, the density of neutral hydrogen atoms is high enough, on average, to cause complete Gunn-Peterson absorption troughs. But long wavelength fluctuations can make some lines of sight passing through regions where the GP absorption are low. Although these events are rare, they are not negligible because the PDF of density distribution is long-tailed. In this case, the large fluctuations of τ are directly determined by $(d \ln \tau/dz) \gg 1$, regardless the inhomogeneity of the UV background.

We also calculate the statistical properties of Lyβ and γ transmitted fluxes. They have the similar behaviors as those of Lyα. Since the absorption section of Lyβ and γ are smaller, the spectra would be more sensitive to the UV background. They could be used as better constraints on the UV background. However, the current data are still not rich enough to provide an effective comparison with simulation samples.

We conclude that in spite of the Lyα absorption spectra at $z \simeq 6$ show very different features from those at $z < 4$, the IGM is probably still in the similar state as $z < 4$, i.e., it is highly ionized by a spatially uniform UV background. The abnormal statistical features of the Lyα transmitted flux at $z \simeq 6$ are mainly inherited from rare events corresponding to the long-tails in the PDF of the IGM density field. This picture is consistent with the other types of observations such as the luminosity function of Lyα emitter which keeps almost constant between redshift $z = 5.7$ and 6.5 (Malhotra & Rhoads 2004), and the latest polarization map of CMB which implies that complete reionization may have already occurred at $z = 7$(Page et al. 2006). Because non-Gaussianity, such as spiky structures, intermittency etc. is sensitive to long-tailed events, our model can be effectively tested with the non-Gaussianity of the

Lyα transmitted flux when more data at high redshifts become available.

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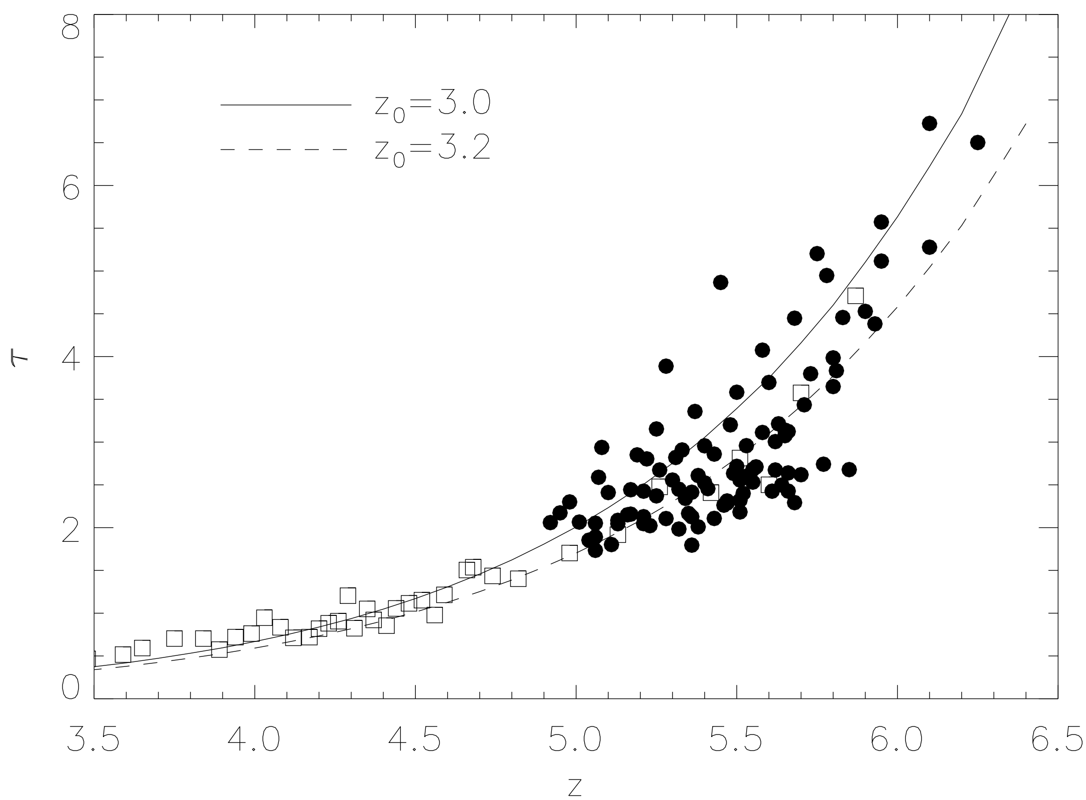

Fig. 1.— $\tau(z)$ vs. z in the redshift range from $z = 3.5$ to $z = 6.4$. The observed data at low redshift are from Songaila & Cowie (2002)(square) and $z > 5$ from Fan et al. (2006) (filled dot). The lines are the mean over 1,000 simulation samples ($z < 5$) and 2000 samples ($z > 5$). The variance of the simulation sample is given in Figure 2. The solid line is for $z_0 = 3.0$ and the dashed for $z_0 = 3.2$ in Eq. 2.

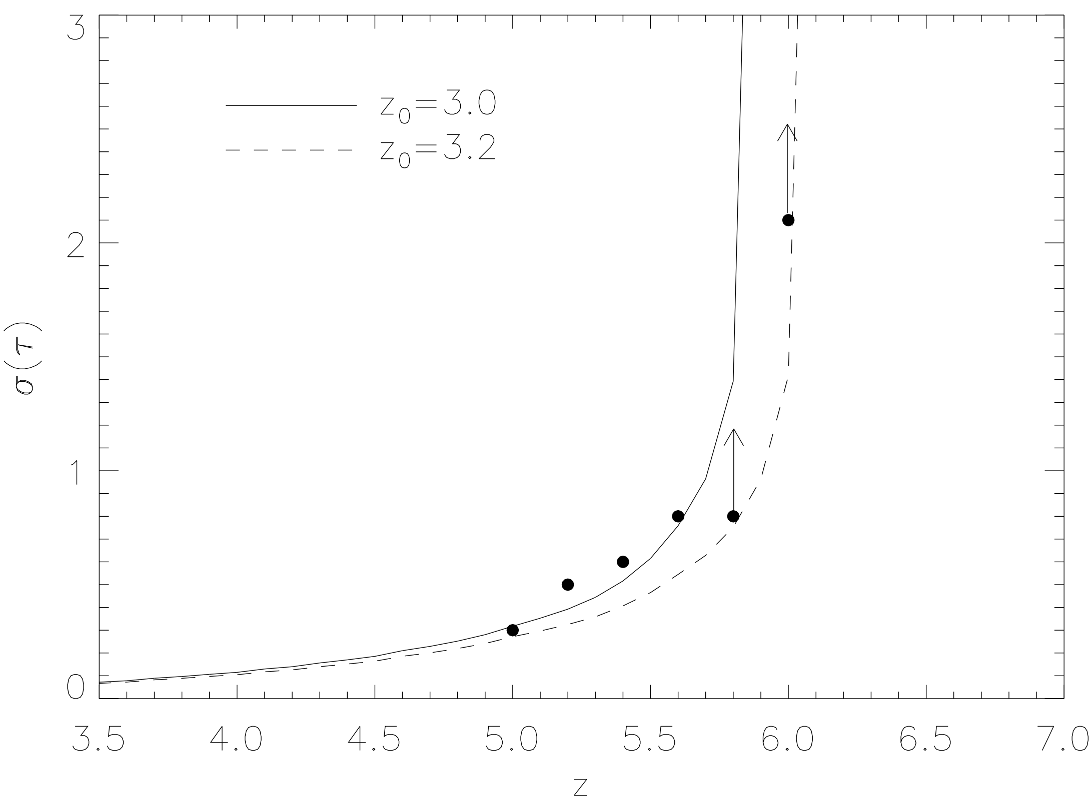

Fig. 2.— The variance $\sigma(\tau)$ as a function of z. The observed data points are taken from Fan et al. (2006). The simulation samples are the same as Fig. 1.

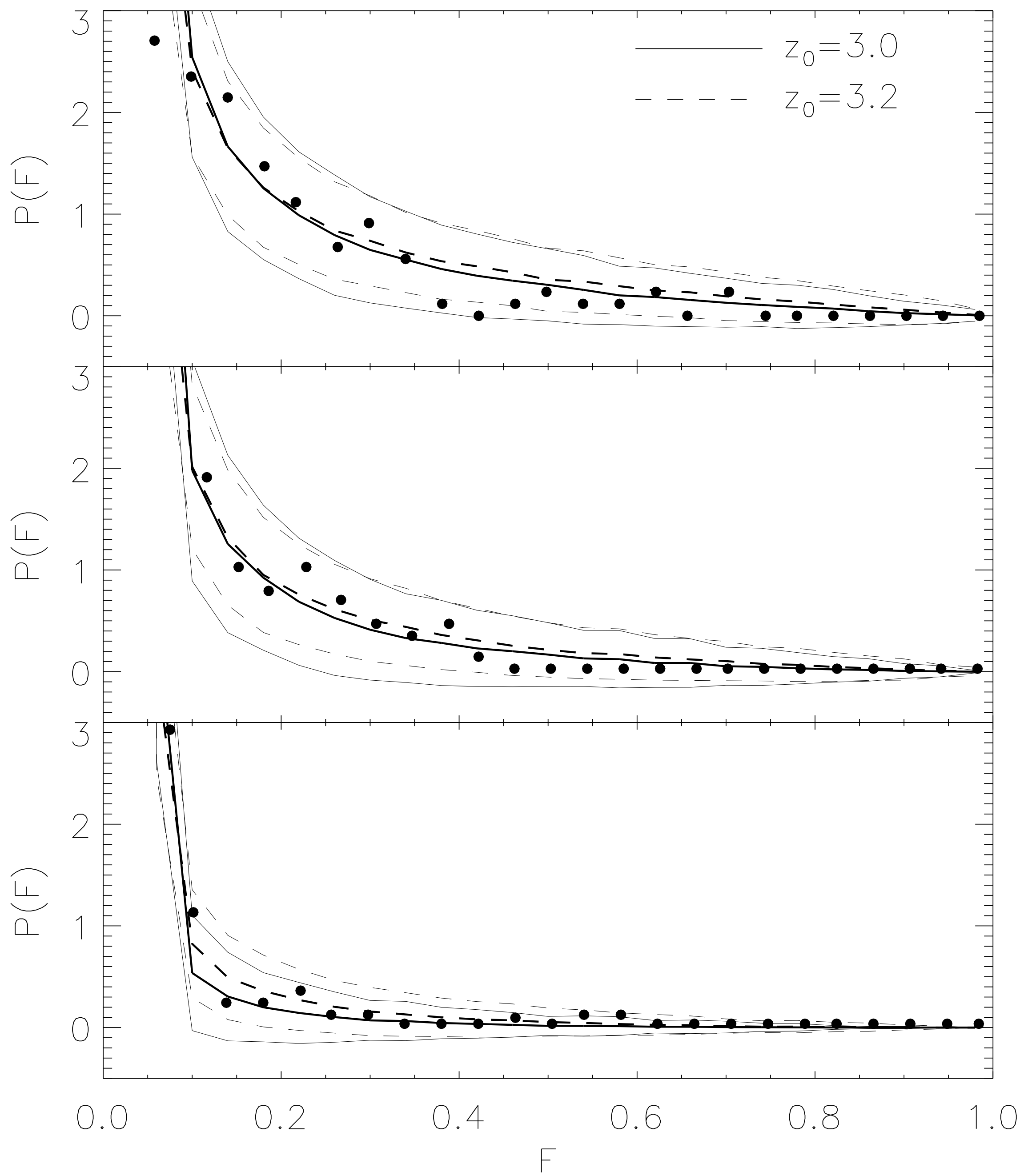

Fig. 3.— Probability distributions of the transmitted flux at redshifts $z = 5.5$ (top), 5.7(middle) and 6 (bottom). The observed data are from Fan et al. (2002). The simulation samples are the same as Fig. 1. The dark and light solid lines are for $z_0 = 3.0$ and their 1-σ error, respectively. The dark and light dashed lines are for $z_0 = 3.2$.

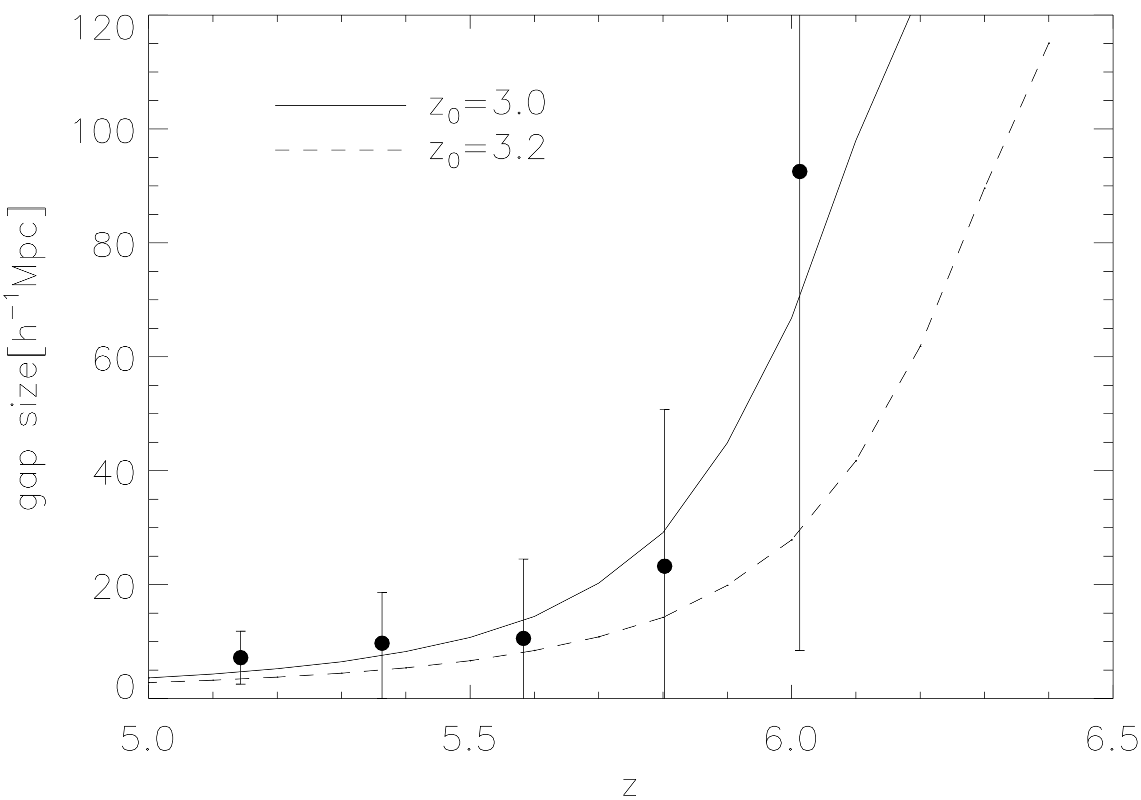

Fig. 4.— The mean size of dark gaps with $\tau > 2.5$ as function of z. The observed data points are from Fan et al. (2006). The simulation samples are the same as Fig. 1.